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# Application of Transform Fourier for Dynamic Control of Structures with Global Positioning System

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***Abstract*—**Given the evolution of viaducts, structural health monitoring requires more complex techniques to define their state. two alternatives can be distinguished: experimental and operational modal analysis. Although accelerometers or Global Positioning System (GPS) have been applied for the monitoring of structures under exploitation, the dynamic monitoring during the stage of construction is not common. This research analyzes whether GPS data can be applied to certain dynamic geometric controls of evolving structures. The fundamentals of this work were applied to the New Bridge of Cádiz (Spain), a worldwide milestone in bridge building. GPS data were recorded with an interval of 1 second during the erection of segments and turned to the frequency domain with Fourier transform. The vibration period and amplitude were contrasted with those provided by the finite element model, with differences of less than 10%, which is admissible. This process provides a vibration record of the structure with GPS, avoiding specific equipment.

***Keywords*—**Fourier transform, global position system, operational modal analysis, structural health monitoring.

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## I. Introduction

THE historical evolution of civil engineering is making viaducts increasingly longer, higher and slimmer [1], and therefore, increasingly demanding in terms of control during construction. During its stages of construction and exploitation, a conventional structure is characterized by being an elastic ensemble which is deformed by direct (wind, service overloads, etc.) or indirect solicitations (thermic actions, phenomena of retraction, etc.). These loads generate in the built model efforts and stresses which the structure must resist within the safety limits set [2].

According to the stress field equations, stresses, deformations and deflections are related. Hence, the knowledge of the deformation through the measurement of displacements is an essential source of information to control the resistance of the ensemble, and to make decisions in cases of non-expected behaviours [3]. It is worth clarifying that this research is focused on the vertical component, although its considerations can be applied to the two components of the planimetric domain. Displacements can be determined through different devices and methods [4], although this research proposes obtaining them with GPS techniques, which have become reliable [5].

The geometric control of bridges and viaducts can be considered in two ways, either within the static or the dynamic fields. The first one considers that the loads imposed on the structure, which define its displacement, are constant or their variation in time and space is negligible [6]. The second alternative assumes that the actions imposed on the structure vary within time and/or space. Therefore, it has a dynamic character, and the resulting inertial forces must be considered for the calculations. Nowadays, there are many studies about the measurement of vibrating movements with accelerometers [7], but only a few that assess the suitability of GPS or other GNSS alternatives for that purpose [8]-[13]. In all of these cases, only the stage of exploitation of the structure is considered. The dynamic control of the structure during the building process, which is the stage of interest for the development of this work, is not that common, neither with accelerometers nor with GPS, as the legal framework of construction does not require monitorization until the beginning of the exploitation stage. Although the works usually count with monitoring systems that include GPS devices, they are only applied to develop routine geometric and static checks, for which the technique is well established [14].

The processes for the geometric controls with GPS have rapidly evolved due to the research that has emerged during recent years: data management through filtering [15]; low cost GPS [16], determination of mean amplitude of small-scale [17], Chebyshev filter [10], Kalman filter [18], etc. This research aims to take another step, as it highlights the possibility to develop dynamic controls with GPS, especially during the construction of flexible evolving structures. It also offers the advantage of registering a record of the structure that allows making decisions in case of problems that could happen during its stage of construction and even its useful life

This research develops the process to monitor with GPS structures under construction, which could lead to know it as "Operational Modal Analysis in the Construction of Evolving Structures". A structure usually has a fundamental frequency which is largely distinguished from the rest, especially if the structure is very flexible. This frequency and, therefore, the period, basically depend on the inertia. Hence, they depend on the rigidity and the mass of the structure. Conclusions about mass and rigidity can be obtained through the frequency.

An evolving structure is built in different stages, and its flexibility is high. This work aims to obtain the period of vibration of an evolving structure for each stage by means of GPS techniques, and to compare them with the theoretical

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periods. This will provide a register of the most representative construction stages and their correct development. Hence, if any difference between the theoretical and actual periods of vibration occurred, it would be determined in real time, due to the simple discrepancy between the theoretical and real periods of vibration.

During construction, the types of evolutionarily-built flexible structures (thrust, incremental launching, etc.) have periods and amplitudes which are great enough to be measured with devices such as GPS [19]. Hence, if there is an obligation to develop classical monitoring of deformations during construction, for which GPS is usually applied, an adequate recording interval and the subsequent treatment of data with an appropriate algorithm will allow obtaining the periods of vibration of a structure in real time, without any other instrumental. Fig. 1 shows how the vibration occurs during construction.

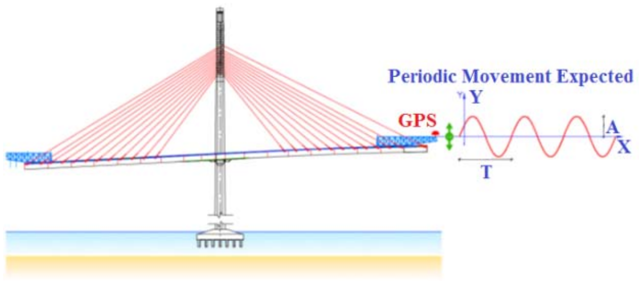


Fig. 1 Simulation of vibration during the process of construction

It is worth noting that the period is intrinsic to a certain structural configuration and, independently of the amplitude, the result is always a constant value. For example, the damping of a certain structure will reduce the amplitude, but the period will remain unaltered. For that reason, the dynamic monitoring of the structure can be developed through the control of the period.

## II. Materials and Methods

### A. Instrumental

The GPS devices that are proposed for this work are two high precision GNSS receivers for auscultation. On this purpose, all the manufactures provide series which are specially designed and constructed for applications of real-time auscultation, so they can be considered as suitable for the intended aim of this research. The ideal situation implies the availability of a triple-frequency antenna, which is compatible with GPS, GLONASS, Galileo, Compass and SBAS signals. This instrumental features adequate specifications to guarantee relative positioning by means of differential observations in post-processing with accuracies of the order of 2 mm+ 2 ppm, and 5 mm + 5 ppm when working in real time.

Real-time GPS observation is widely developed in conventional literature. It requires the following set up, which provides the data that have been adopted as starting material for the development of this research:

– A device, known as reference, is placed on a pillar that is located out of the area of influence of the structure. The coordinates of that pillar have been previously defined in the adopted system of reference, which allows determining the differential correction that is transmitted to the device in real-time each second.
– The second device is known as mobile, and it is set on the launching gantry by means of a support which is properly welded to the structure, in order to join them together: both the antenna and the board experiment the same movement. This device obtains the differential corrections via radio and applies them to the observations. Firstly, it develops a starting period with the calculation of integer ambiguities through On the Fly (OTF) techniques that allow defining them in motion. Fig. 2 shows the device location and therefore the exact place where the test is done. The location with the maximum expected displacement is generally sought. In evolving structures or during construction, the test can be performed in several points, depending on the different construction stages

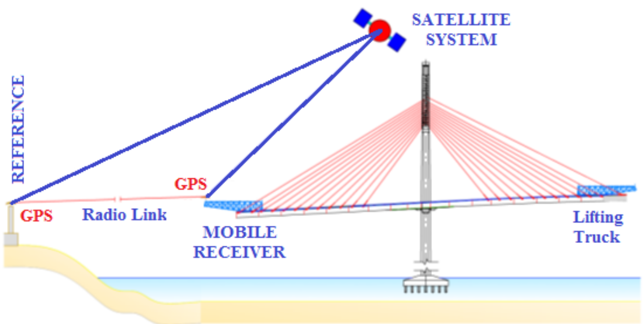


Fig. 2 GPS scheme applied during the construction of Bridge of Cádiz

The main issue that can be highlighted about the GPS observables is the period of time that occurs between two consecutive records, which are also known as epochs. The devices allow selecting that interval and, for this research, they were set to record data every second. This depends on the expected vibration, it being possible to register data each 0.05 seconds.

In the real-time surveying process, the device automatically registers in files the coordinates of the position of the antenna for each second, firstly in WGS84 and later, in the reference system set. The results are generally kept in a file with the exchange format Rinex, along with other more or less representative parameters, such as the number of satellites, the expected accuracy, date, time, etc.

### B. Modal Data Extracted from Finite Element Model

The interpretation of the results requires a theoretical model of the behavior of the bridge. On that purpose, modal data extracted from the finite element model are available. The model can be implemented for any structural typology, and both for linear and non-linear behaviors. For the linear behavior, which is considered in this research, a spatial discretization of the bridge (obtaining a model with N degrees of freedom, where N is a discrete number) and also a temporal discretization for different times were developed. Therefore, a direct integration analysis of the whole model, or a modal analysis, is held. The following expression must be solved in any case:

$$p(t) = [K]y + [C]\frac{dy}{dt} + [m]\frac{d^2y}{dt^2} \tag{1}$$

Two different ways can be applied to face its resolution, as it is possible to adopt the time or frequency domains. Both options are equivalent and the selection of one or another depends on the parameter to be calculated.

Considering the data from the model of the bridge for the position of 27th September, 2014, in the slab 11D P-12 and before the blocking, which were obtained with the software Sofistik, the following values were obtained for the studied position:

- Modal form, 1, the Bending of the tower results f=0.075 Hz.
- Modal form 2, the Torsion of the tower is f=0.090 Hz.
- Fundamental period of 13.33 s.

These data will be applied to contrast those obtained from the previous spectral analysis.

### *C. Methodologic Fundamentals*

In this research, the dynamic analysis of structures is referred to that of the little oscillations or vibrations that the structure can suffer around its position of static equilibrium. It is held by means of its spectral analysis in the frequency domain and, therefore, it is based on the decomposition of the physical phenomenon in separate components with respect to the frequency. Considering this work, the analysis consists on the decomposition of the vibrating movement that naturally occurs in the board into its fundamental frequencies. It also provides added knowledge about the structure to avoid resonance phenomena or overloading, to define the goodness of its dynamic behavior, etc., and guarantees a situation of optimal control during the construction stage.

In order to develop this dynamic control of the structure, it is possible to work in the time domain, so that the structural parameters can be obtained by considering time as a variable, or in the frequency domain. In the second case, the structural parameters are determined by considering as variables the different frequencies in which the harmonic movement of the board can be decomposed [20]. Fig. 3 shows the meaning of temporal domain and frequency in a graphical way.

The mathematical instrument applied to obtain all the required information is the Fourier transform [21], which provides the details about the frequency of a certain function, whose determination over time is known. It is also possible to develop an inverse transformation, that is to say, to pass from the frequency domain to the temporal field.

It is worth distinguishing between Fourier Series and Fourier Transform. The first one allows decomposing any temporal distribution into a summation of spatial sine distributions, while the second one can be applied when working with aperiodic signals. The conditions under which a periodic function can be developed as a Fourier series are given by Dirichlet's Theorem [22].

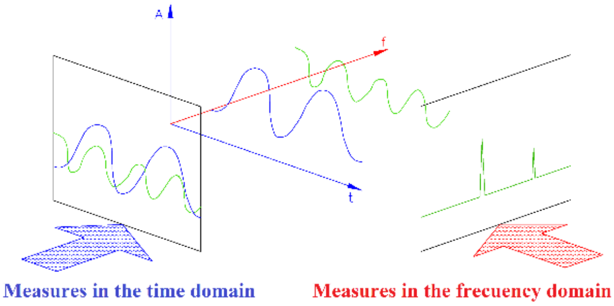


Fig. 3 Meaning of time and frequency domains

The general form of Fourier series can be expressed in its complex exponential form, by substituting sine and cosine functions with their exponential forms:

$$f(t) = a_0 + \sum_{j=1}^{\infty}\left[a_j\frac{e^{i\frac{2\pi}{T_0}jt}+e^{-i\frac{2\pi}{T_0}jt}}{2} + b_j\frac{e^{i\frac{2\pi}{T_0}jt}-e^{-i\frac{2\pi}{T_0}jt}}{2i}\right] \tag{2}$$

The determination of Fourier Transform for non-periodic functions in an interval (a,b), requires the recovery of the complex formulation of Fourier series, in which it is finally obtained that:

$$\eta(t) = \sum_{n=-\infty}^{\infty} d_n e^{i\omega_n t} \tag{3}$$

where:

$$d_n = \frac{1}{b-a}\int_a^b \eta(t)e^{-i\omega_n t}dt \tag{4}$$

The following expression is obtained:

$$f(t) = \sum_{-\infty}^{\infty}\frac{\Delta\omega}{\sqrt{2\pi}}\left(\frac{1}{\sqrt{2\pi}}\int_a^b \eta(t)e^{-i\omega_n t}dt\right)e^{i\omega_n t} \tag{5}$$

Discrete Fourier transform (DFT) can be mathematically defined with (6) and (7):

$$f(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} F(f)e^{i2\pi ft}df \tag{6}$$

$$F(f) = \int_{-\infty}^{\infty} f(t)e^{-i2\pi ft}dt \tag{7}$$

When applying computer tools, these expressions are not easy to program and therefore to solve. This is mainly due to the fact that they adopt infinite values in a finite interval of time and frequency. Hence, it is necessary to adapt the expressions to others that allow programming them. Due to this, DFT arises as a simplification for numerical calculation. On that purpose, it is necessary to sample the signal function in a way that, among the infinite values that it comprises, a discrete number of them, which are separated from each other by a constant interval of the independent variable, is taken. The adequate sampling is given by Nyquist-Shannon theorem.

Considering the case proposed in this work, there is not a continuous function in a certain interval, but the discrete records of the data acquired with GPS and equal intervals (Δt) during the stage of erection of a segment.

Fourier transform is a discrete function of N data which are separated by intervals of regular periods. Hence, DFT can be numerically obtained as a sequence by ignoring the dependent variable during the calculations. This way, the time consumed by a computer to calculate a DFT is proportional to $N^2$.

Fast Fourier transform (FFT) is simply an algorithm to obtain Discreet Fourier Transform, with the advantage of noticeably reductions in the calculating time of the computer and the rounding error, through an optimization of the number of required operations. In a numerical way, it can be said that the calculating time is reduced by

$$\frac{log_2 N}{N} \tag{8}$$

where N is the number of samples and Starting with Discreet Fourier Transform:

$$X(k\omega_0) = \sum_{k=0}^{N-1} x_0(nT)e^{-2\pi in\frac{k}{N}} = \sum_{m=0}^{N-1} x_0(nT)W^{nk} \tag{9}$$

It can be expressed in its matrix form:

$$\begin{bmatrix} X(0) \\ X(1) \\ X(2) \\ X(3) \end{bmatrix} = \begin{bmatrix} W^0 & W^0 & W^0 & W^0 \\ W^0 & W^1 & W^2 & W^3 \\ W^0 & W^2 & W^4 & W^6 \\ W^0 & W^3 & W^6 & W^9 \end{bmatrix} \begin{bmatrix} x_0(0) \\ x_0(1) \\ x_0(2) \\ x_0(3) \end{bmatrix} \tag{10}$$

$$X = W^{kn}x_0 \tag{11}$$

In order to solve this system in N unknowns, N^2 multiplications and N(N-1) sums are required; that is to say, 16 multiplications and 12 sums in the field of complex numbers. FFT is aimed to reduce the total number of operations in a drastic way. The most applied alternative is the Cooley-Tukey algorithm, in which the chosen number of samples must be a power of 2, that is to say, $N = 2^n$, where n is an integer.

## III. Calculations

### *A. Application to the New Bridge of Cádiz: General Description of the Structure*

The structure in which the test is developed is the second access to the Spanish city of Cádiz. The most emblematic element in the project of the New Access to Cádiz is the Bridge over the Bay, which was inaugurated on 24th September, 2015. The board of the Bridge accommodates a highway road with four lanes (two lanes for each traffic direction) and a platform which is reserved for tramway traffic. The bridge is 3,157 meter-long and it comprises 37 piers, with the first 12 over the sea. The two main diabolo-shaped pylons (piers 12 and 13) stand out among the piers. From number 1 to number 17, the rest of the piers belong to the "palm tree" typology, and from number 18 on, they transform into arched piers to allow passing below them, as it can be appreciated in Fig. 4.

Fig. 4 Aerial view of the completed Bridge of Cádiz

Taking into account the support, section and typology of the board, the bridge can be divided into four parts:

– The access section to Cádiz, which is 654 meter-long and has 75 meter-long spans. This section was constructed with the incremental launch process.
– Removable section, which is 150 meter-long, and will allow the eventual traffic of boats with unusual gauging, over 69 meters.
– Cable-stayed section, which is developed along 1180 meters with a main span between towers of 540 meters. It leaves an available height below the board of 69 meters.
– Final concrete section of 1182 meters, which is constructed with formwork and whose main spans are 75 meter-long.

The geometric control of the board was developed in the cable stayed section during the following stages: the erection and assembling of the segment, the intermediate controls during the cycle and, finally, the cable tensioning.

### *B. Modal Data Extracted from Finite Element Model*

The use of instrumental to obtain the dynamic values in the Bridge of the Bay of Cádiz was planned for both the construction and exploitation stages. Dynamic instrumentation had to be reinforced during the period of construction, so as to avoid the problems of dynamic resonance that could happen during the erection of the segments, due to coupling between the period of the waves and the fundamental period of the cantilever board. The instrumental that was planned for the stage of exploitation comprised 48 sensors (34 accelerometers, five anemometers, four temperature probes and five wind vanes). These sensors were distributed along the different parts of the bridge according to the parameters to be monitored.

### *C. Description of the Test*

Given the large amount of data that were obtained from the different tests during construction stage of such a massive structure, only those provided by a sole test (centered on segment P-12, slab 11-D, see Fig. 2) are shown. This makes clear that, from a structural point of view, the tests should be done during any relevant stage to achieve a control that is significant enough. For the development of the test, the GPS devices were set as described in the "Instrumental" section (Fig. 2), and data were acquired according to the following features:

- Day: $27^{th}$ September, 2014
- Start time: 10:33:18
- End time: 12:21:03
- Number of collected data: 4,861 records
- Time interval between consecutive data: 1 s.

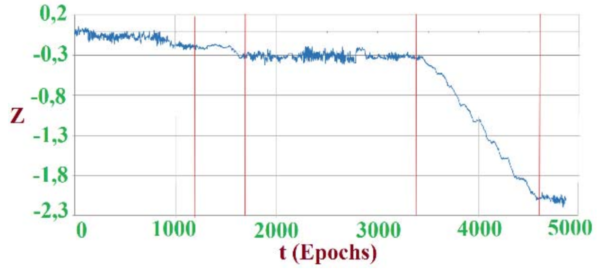


Fig. 5 Relative height of the launching nose over time

In the first instance, the planimetric and altimetric coordinates and the epoch were extracted from the stored data. The last two parameters were the main data required for the dynamic analysis that is proposed in this research. Fig. 5 was obtained by plotting the 4,861 records collected with GPS in a Cartesian system, where the Z-coordinate (Y-axis) is represented against time or epochs (X-Axis).

In light of the figure, five perfectly differentiated areas can be noticed (Table I). These zones require an independent analysis, and can be generally classified as:

- Zone 1: From the beginning to epoch 11:05:49, this zone comprises 1280 records. The movement of the end of the board seems to be free: despite specific actions due to several operations developed during the works, the frequency is natural.
- Zone 2: From epoch 11:05:51 to epoch 11:13:08. Its 256 records show heterogeneous movements of the head, which are due to external forces applied on it, such as cable tensioning, wind gusts, etc. They make the head vibrate in a non-natural way.
- Zone 3: From epoch 11:13:10 to epoch 11:51:47. Its 1792 points show a similar behavior to that of Zone 1.
- Zone 4: From epoch 11:51:48 to epoch 12:15:40. 1152 records allow noticing that the board suffers a marked decline of about 2 meters. This is due to the erection of the subsequent segment, which is placed on the barge.
- Zone 5: From epoch 12:16:08 to epoch 12:21:03. 256 records are enough to recover a homogeneous oscillatory movement, had the segment become independent with respect to the barge, and been fixed to the bridge.

Data analysis was developed on the basis of independent zones, obtaining the fundamental period for each of them. Considering the cases with absence of punctual external stresses that alter the period (Zone 1, Zone 3 and Zone 5), and after its calculation, it was verified whether the period was similar to that obtained in the finite element model, and if it recovered the original value when the external stresses that were forced on the board disappeared.

TABLE I
TEMPORARY ZONING OF GPS DISCRETE OBSERVABLES

| Zone | Initial epoch | Final epoch | Mean height (z) | nº records |
|---|---|---|---|---|
| Zone 1 | 10:33:18 | 11:05:49 | 84.113 | 1280 |
| Zone 2 | 11:05:51 | 11:13:08 | 84.017 | 256 |
| Zone 3 | 11:13:10 | 11:51:47 | 83.895 | 1792 |
| Zone 4 | 11:51:48 | 12:15:40 | 82.998 | 1152 |
| Zone 5 | 12:16:08 | 12:21:03 | 82.114 | 256 |

The data processing that was applied in the domain of time to Zone 1 is described below. The values obtained for the rest of the zones are subsequently shown in "Results". In the first instance, with the aim of correctly delimiting the data that were not subjected to external stresses in Zone 1, and therefore to perform the later analysis with the suitable algorithm (it should comprise data sets that comply with 2^n), groups of correlative records from 128 observations (27) were selected. Table II could be obtained from them with a subzoning within Zone 1.

TABLE II
SUBZONING OF DISCRETE GPS OBSERVABLES IN ZONE 1

| Zone | Initial Epoch | Final Epoch | Mean height | nº records |
|---|---|---|---|---|
| Zone 1-1 | 10:33:18 | 10:35:44 | 84.209 | 128 |
| Zone 1-1 | 10:35:45 | 10:46:17 | 84.155 | 128 |
| Zone 1-1 | 10:46:18 | 10:48:39 | 84.139 | 128 |
| Zone 1-1 | 10:48:41 | 10:51:02 | 84.139 | 128 |
| Zone 1-1 | 10:51:04 | 10:53:27 | 84.136 | 128 |
| Zone1-2 | 10:53:27 | 10:55:49 | 84.138 | 128 |
| Zone 1-3 | 10:55:50 | 10:58:10 | 84.119 | 128 |
| Zone 1-4 | 10:58:12 | 11:00:33 | 84.061 | 128 |
| Zone 1-5 | 11:00:34 | 11:02:55 | 84.025 | 128 |
| Zone 1-5 | 11:02:57 | 11:05:49 | 84.006 | 128 |

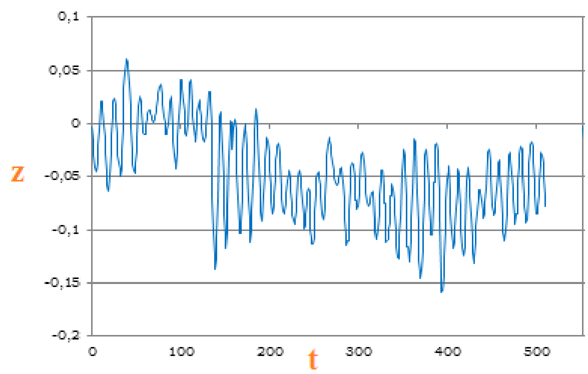


Fig. 6 Time series from 10:33:18 to 10:51:02, 24/09/14

A homogeneus graphic (Fig. 6) is obtained by plotting the data corresponding to Zone 1-1. They are limited to 512 records $(2^9)$ due to algorithm constraints. Fig. 6 corresponds to records from 10:33:18 to 10:51:02.

In this way, Zone 1 can be divided into five zones that, as it is logical, provide different results. That said, the tendency that could be extracted from the graph at first glance shows the typical pitch of a sinusoidal wave on the panel, where all the frequencies are represented. The main frequency corresponds to that of the cantilever. This analysis was only performed for homogeneous zones.

The algorithm was then applied to three zones which are clearly differenced and free from external stresses. Therefore, they can be considered within the parameters explained for this monitoring of evolving structures. The obtained frequencies were subsequently contrasted with those determined with the finite element calculation model of the bridge

## IV. Results

Table III shows the results provided by the application of the transform to the frequency domain in Zone 1. It allows observing the resulting frequency and period.

FFT had been applied to the observables provided by GPS, Fig. 7 was obtained by plotting frequency and amplitude.

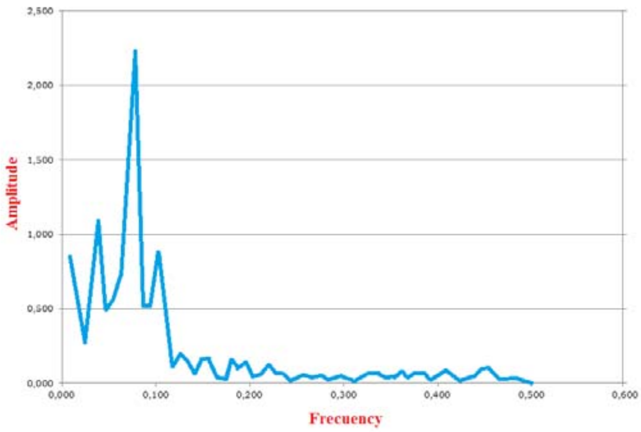


Fig. 7 Graphic representation of Frequency against Amplitude

TABLE III
Dynamic Parameters Obtained in Zone 1

| Fourier Analysis for the discrete data series | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Number of data in the series: | | | 128 | Frequency: | 0.078 | Hz |
| | Arithmetic mean of the series: | | | 84.155 | Period: | 12.8 | seg |
| | Date: | | | 27/9/14 | Initial Epoch | 10:35:45 | |
| | | | | | Final Epoch: | 10:46:17 | |
| Time | Epoch | Series | Elevation | Fourier Transform | Frecuency | Magnitude | Period |
| 0 | 10:35:45 | 84.1971 | 0.042 | 0 | 0.000 | 0.000 | |
| 1 | 10:35:46 | 84.2051 | 0.050 | -0.377249-0.765598i | 0.008 | 0.853 | 128.000 |
| 2 | 10:35:48 | 84.2201 | 0.065 | 0.319877-0.482628i | 0.016 | 0.579 | 64.000 |
| 3 | 10:43:18 | 84.2201 | 0.065 | 0.266662-0.064026i | 0.023 | 0.274 | 42.667 |
| 4 | 10:43:19 | 84.2381 | 0.083 | 0.625614-0.143592i | 0.031 | 0.642 | 32.000 |
| 5 | 10:43:20 | 84.2381 | 0.083 | 0.739219-0.798017i | 0.039 | 1.088 | 25.600 |
| 6 | 10:43:21 | 84.2291 | 0.074 | 0.392114-0.302891i | 0.047 | 0.495 | 21.333 |
| 7 | 10:43:22 | 84.2071 | 0.052 | 0.511704-0.195635i | 0.055 | 0.548 | 18.286 |
| 8 | 10:43:24 | 84.1371 | -0.018 | 0.685743-0.177628i | 0.063 | 0.708 | 16.000 |
| 9 | 10:43:25 | 84.1071 | -0.048 | 0.999750-0.964428i | 0.070 | 1.389 | 14.222 |
| 10 | 10:43:26 | 84.0841 | -0.071 | -1.445734-1.681944i | 0.078 | 2.218 | 12.800 |
| 11 | 10:43:27 | 84.0711 | -0.084 | 0.354672+0.386069i | 0.086 | 0.524 | 11.636 |
| 12 | 10:43:28 | 84.0811 | -0.074 | -0.507523+0.114739i | 0.094 | 0.520 | 10.667 |
| 13 | 10:43:29 | 84.1031 | -0.052 | -0.499799+0.736155i | 0.102 | 0.890 | 9.846 |
| 14 | 10:43:30 | 84.1381 | -0.017 | 0.005338+0.563333i | 0.109 | 0.563 | 9.143 |
| 15 | 10:43:32 | 84.1991 | 0.044 | 0.115095+0.041221i | 0.117 | 0.122 | 8.533 |
| 16 | 10:43:33 | 84.2161 | 0.061 | -0.142033-0.144548i | 0.125 | 0.203 | 8.000 |
| 17 | 10:43:34 | 84.2201 | 0.065 | -0.161090+0.013195i | 0.133 | 0.162 | 7.529 |
| 18 | 10:43:35 | 84.2091 | 0.054 | 0.020421+0.069322i | 0.141 | 0.072 | 7.111 |
| 19 | 10:43:36 | 84.1851 | 0.030 | 0.160126-0.022566i | 0.148 | 0.162 | 6.737 |
| 20 | 10:43:37 | 84.1581 | 0.003 | 0.036649-0.176095i | 0.156 | 0.180 | 6.400 |
| 21 | 10:43:39 | 84.1221 | -0.033 | -0.023329-0.039063i | 0.164 | 0.045 | 6.095 |
| 22 | 10:43:40 | 84.1041 | -0.051 | -0.016389+0.019933i | 0.172 | 0.026 | 5.818 |
| 23 | 10:43:41 | 84.0911 | -0.064 | 0.132872+0.097666i | 0.180 | 0.165 | 5.565 |
| 24 | 10:43:42 | 84.1061 | -0.049 | 0.093688-0.067181i | 0.188 | 0.115 | 5.333 |
| 25 | 10:43:43 | 84.1341 | -0.021 | -0.010068-0.152870i | 0.195 | 0.153 | 5.120 |
| … | … | … | … | … | … | … | … |

If frequency and amplitude are represented for each one of the zones and subzones, it can be concluded that there are two moments that must be dismissed to obtain the board period, [10:53:27 to 10:55:49] and [10:58:12 to 11:00:33]. On the other hand, Fourier analysis can be applied to zone 1-1 with 128 or 512 records (28 or 29), in order to increase the accuracy of the result. Table III shows the results that have been obtained from 512 records belonging to the interval [10:33:18 to 10:53:27].

The application of the same process for each predefined sub-section provides the following results:

- Zone 1: The analysis was developed with sets of 512 records, to which Fourier transform was applied considering homogeneous enough areas. It provides a frequency of 0.074 Hz and a period of 13.5 seconds.
- Zone 3: The use of the same process in Zone 3, with the application of Fourier Transform to sets of 512 records which were selected in homogeneous enough areas, provides a frequency of 0.082 Hz and a period of 12.2 seconds.
- Zone 5: The analysis of this Zone, which implies the application of Fourier Transform to sets of 256 records, provides a frequency of 0.090 Hz and a period of 11.9 seconds.

## V. Discussion

The analysis and comparison of the results obtained in the different areas, which are shown in the previous section, allows considering them as valid with respect to that obtained with the finite element model, 13.33 s. The differences, which are lesser than the 10% set for the project, are considered as small. Despite the error that is produced by setting the finite element model (the tool itself is not free from errors), they can be considered to be minor for this research, and therefore, they can be disregarded for the development of the analysis. The differences can be due to the uncertainty of the GPS survey itself, and to the constructive differences that can exist between the theoretical project and the really executed one.

In all the results that have been obtained for the fundamental period of the board, the differences with respect to the theoretical value can be considered as comprised within normal ranges, since both the board under construction and the pylon that supports it are affected by different circumstances that justify this little variation for each case, such as:

- A little difference can be attributed to the uncertainty of the GPS survey.
- Discrepancies between the theoretical project and the really executed work, which would imply little variations with respect to the values extracted from the theoretical model.

All these factors lead to justify the differences existing between the period provided by the model and that obtained from GPS observations with their corresponding Fourier analysis for discrete series as assumable, since they are lesser than 10%. It can be stated that both the instrumental and the methodology proposed for this research are valid, because they are able to determine the fundamental frequencies of the structure, with assumable uncertainties.

A weakness of this research is related to the absence of contrast with respect to other instrumental. This is due to the fact that the devices required for it had not been foreseen even for such a singular structure as the one that has been considered in this work, which highlights the scarce development of dynamic monitoring in evolving structures.

## VI. Conclusions

The use of the records acquired by means of GPS at the New Bridge over the Bay of Cadiz with a recording interval of 1 second has demonstrated that the development of a dynamic check of the structure is possible. This check consists in the measurement of the main frequencies of vibration during the evolving process of construction, to confront them with the theoretical values. The method of resolution is developed with a spectral analysis: As the obtained data, height-time, represent a function in the domain of time that can be transferred to the frequency domain by using Fourier Transform, the modal parameters of the structure can be subsequently obtained.

Although several approaches for the dynamic monitoring of finished structures by means of GNSS can be found in scientific literature, GPS has not been applied to analyse their behaviour during the stage of construction, which is the main interest and contribution of this work. Therefore, this research proposed the development of the dynamic check of an evolving structure by means of an Operational Modal Analysis during its stage of construction, with the environmental excitation (wind), by the application of raw GPS data. This article has demonstrated that the comparison of the results with those obtained with the theoretical calculation model provides differences lesser than 10%, which are perfectly assumable.

The proposed methodology generates a series of strengths that can be highlighted:

- Due to their precision, availability and economy, the use of GPS receivers allows the dynamic monitoring of evolving structures with great flexibility, especially during the stage of construction, which is a spearhead that has not been fully investigated.
- The availability of these observables during construction permits checking the sections under extreme conditions. In addition to this, they provide a higher guarantee of safety and structural quality, without increasing costs, as the applied instrumental can be included within the surveying activities to be developed during the construction of the structure itself.
- The proposed process implies a new avenue in the field of Operational Modal Analyses, as it allows analyzing any type of structure without needing specific devices. In addition to that, the proposed methodology is not considered as destructive, and therefore, it is completely innocuous to the structure. By getting advantage of environmental loads (wind), there is no need to include any external exciter element, which would increase the operating costs and could overload the structure.
- The collection of dynamic information in the domain of time, that is to say, from the acquisition of displacement data, offers advantages with respect to the traditional way, which implies the measurement of accelerations. It initially avoids the double integration that is required from the accelerations. It provides a higher precision, and avoids the need to work with accelerometers. Moreover, the monitoring is developed in a continuous way and the

information can be processed in real time.

- The proposed methodology allows checking each construction stage of the structure as it is built, and therefore, it provides knowledge about their degree of goodness. If a difference between the theoretical and the real vibration periods exists, the occurrence of an anomaly during construction (such as a section with an error of execution, a poorly-performed welding, an excess of concrete on the slab, etc.) is known in real time. Therefore, that a high grade of control during execution is achieved.

The obtained results fully validate the process, which is equivalent to the development of a dynamic loading test for each construction stage of the structure, without any more data or costs that those derived from the use of GPS devices. It also allows determining the geometrical and static control of the structure in a simultaneous way, without needing a Topographic Station.

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